ABSTRACT

Erosion-Corrosion behavior of carbon steel material was investigated under iron carbonate scale forming conditions in a CO₂ saturated environment as it was impinged by CaCO₃ and sand particles. Experimental data were collected with the objective of studying the effect of an imidazoline based inhibitor on reducing CO₂ corrosion of low carbon steel material in erosive environments. The erosivites of sand and CaCO₃ particles were characterized for iron carbonate scale covered steel surfaces and for bare metal steel surfaces. Comparing CaCO₃ and sand erosion data under dry and wet conditions, sand was found to be more erosive than CaCO₃ particles. For the experimental conditions considered, the imidazoline based inhibitor provided greater corrosion protection to the bare metal carbon steel surface than the iron carbonate scale did. Consequently, lower erosion-corrosion material loss was measured with inhibitor than with the protective iron carbonate scale.

Key words: Iron Carbonate Scale (FeCO₃), CO₂ Corrosion, Erosion, Erosion-Corrosion, Sand, Calcium Carbonate Particles (CaCO₃), Inhibited Erosion-Corrosion, Imidazoline based inhibitor
INTRODUCTION

Erosion-corrosion deterioration of carbon steel in the presence of solid particulates is a major issue in oil and gas production. Erosion can significantly influence corrosion by negatively interfering with corrosion mitigation systems, such as when a protective corrosion scale or an inhibitor film is stripped away through solid particle erosion. The combined effect of erosion and corrosion can lead to high corrosion rates, surface pitting, and, ultimately, material failure. Under certain environmental conditions in CO₂ corrosion, which are typically high pH, temperature above 180 to 200°F (82 to 93°C) and low flow velocity, a protective layer of iron carbonate forms on the steel surface. This corrosion product can reduce corrosion rates when the scale completely covers the steel surface. The presence of solid particles, such as sand or calcium carbonate, can strip away this iron carbonate layer, leading to an increase in corrosion rates. In many cases, operators do not rely on scale formation to protect materials, but use chemical corrosion inhibitors to minimize material loss. Corrosion inhibitors, however, are also influenced by flows containing particulates.¹-⁴ Solid particles such as sand and calcium carbonate can reduce inhibitor efficiency through adsorption of inhibitor to the particle surface and by stripping inhibitor from the steel surface.

The effects of sand erosion on the efficiency of corrosion inhibitors have been studied for scale-forming and non-scale-forming environments.¹-⁴ However, a large percentage of oil and gas is produced from carbonate reservoirs where calcium carbonate (CaCO₃) particles can enter into the flow of the produced gas and oil. Currently, little is known about the erosive effects of CaCO₃ particles on the erosion-corrosion of steel in iron carbonate scale forming environments. This paper describes an experimental investigation directed at understanding the influence of CaCO₃ particles on inhibitor effectiveness by comparing the performance of an imidazoline-based inhibitor in a flow containing CaCO₃ particles with the inhibitor performance for a flow containing sand particles. The inhibitor performance is also compared with the performance of iron carbonate scale in reducing CO₂ corrosion under the same conditions. The erosion-corrosion experiments were performed using flow loop set up with a direct impingement configuration in an iron carbonate scale forming environment. Linear polarization resistance and weight loss methods were utilized to experimentally characterize erosion-corrosion rates for both types of solid particles. The composition of the iron carbonate scale was verified by X-Ray diffraction analysis and by scanning electron microscopy.

EXPERIMENTAL PROCEDURE

The experimental approach considered in this research consists of four steps; 1) form iron carbonate scale on carbon steel (UNS® G10180) specimens, 2) characterize erosivity of solid particles under dry and wet conditions, 3) conduct erosion-corrosion tests for pre-formed scale steel and bare steel specimens, and 4) conduct inhibited erosion-corrosion for bare steel specimens. Three different experimental facilities are used to perform these tests. A 3-cell flow loop for scale formation, a direct impingement dry gas erosion testing facility for dry erosion testing, and a single test cell flow loop for wet erosion, erosion-corrosion and inhibited erosion-corrosion testing. Two kinds of solid particles were investigated, calcium carbonate (250 µm) and sand (150 µm) particles. The numbers in parentheses are the average particle diameters. Bare carbon steel specimens were surface finished using sand paper with 68 µm average grain size and subsequently cleaned with acetone before testing.

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* The Unified Numbering System - UNS - developed by ASTM and SAE to relate different numbering systems for commercial metals and alloys
Iron carbonate scale is formed simultaneously on three carbon steel specimens using the 3-cell flow loop (step #1). The flow loop is made of stainless steel material (UNS S31603) and consists of three direct impingement test cells in series, a heated solution tank, and a circulating pump. A schematic of the three-cell flow loop is shown in Figure 1. Iron carbonate scale was formed in a CO₂ gas (20 psi) saturated brine solution at a pH of 5.9, a temperature of 175 °F, (79 °C), and a flow velocity of 9.0 ft/s (2.74 m/s). The test solution was prepared by mixing distilled water with 3% wt. NaCl and 1500 ppm NaHCO₃. The solution was de-aerated using vacuum pump for 2 hours to minimize oxygen concentration to approximately 15 ppb, then the system was pressurized with 20 psi CO₂ gas. After pressurization, the test solution was circulated for at least six hours to reach the desired temperature and pH. A detailed description of the design and operating procedure of the 3-cell flow loop can be found elsewhere.³⁵

An electrochemical linear polarization resistance (LPR) method was used to monitor corrosion rates throughout the iron carbonate scale formation process. The LPR probe is made from a carbon steel (UNS G10180) working electrode, a stainless steel (UNS S31603) reference electrode. The stainless steel flow loop body was used as counter electrode. The working and the reference electrodes are electrically separated by a ceramic coating. The LPR probe is 1.25 inch (3.175 cm) in diameter and located approximately 0.5 inch (1.27 cm) in front of the nozzle exit. The impingement nozzle from which the test solution was aligned with the center of the probe and has an inner diameter of 0.265 inch (0.6731 cm). More details regarding the design of the LPR probe can be found elsewhere.⁶

![Figure 1: A schematic of the 3-cell flow loop](image)

Because the two particles have significantly different hardness, the erosivity of the particles relative to iron carbonate scale and imidazoline based inhibitor were quantified under both dry and wet conditions (step #2). Dry erosion tests were conducted on bare steel and on iron carbonate scale covered surface using dry erosion testing facility. This testing facility consists of
a compressor that acts as a source of air, the carrier fluid, a nozzle that directs particles at the specimen surface at a determined gas velocity, and a specimen holder that can be adjusted at different impact angles and a particle feeder. A schematic of the dry erosion testing apparatus is shown in Figure 2. Two kinds of solid particles are investigated, 150 µm round shaped sand and 250 µm angular shaped CaCO$_3$. Dry erosion tests were conducted at a particle velocity of 23 m/s for both sand and CaCO$_3$ particles. In dry erosion, bare steel and pre-scaled specimens were eroded in a number of successive steps with each step consisting of a fixed mass of particles used for impingement. The mass loss due to material removal by dry erosion is measured for each step. The erosion ratio is expressed by the slope of the curve obtained by plotting the cumulative mass loss versus the cumulative mass of solid particles added. The erosion ratio reflects the erosivity of different particles. A detailed description of the dry erosion testing and solid particles impact velocity measurements can be found elsewhere.$^7$-$^{10}$

![Figure 2: A schematic of dry erosion testing set up](image)

Wet erosion tests were conducted on pre-formed scale specimens under a submerged direct impingement condition using the single test cell flow loop. The single test cell flow loop was similar to the 3-cell flow loop in design and function, but the test section of this flow loop was equipped with a cyclone separator. A cyclone separator keeps solid particles circulating in the test section without flowing through the pump. The single test cell loop consists of a solution tank wrapped with electrical heating tape, a solid particle feeder, cyclone separator, diaphragm pump (Hydra-cell*), electronic flow meter (Paddlewheel**), and the single cell test section. The conventional volume displacement method was adopted along with electronic flow meter to confirm the flow rate. A schematic of the flow loop is shown in Figure 3. The particle feeder of the flow loop is used for introducing solid particles into the flow loop. The pH is monitored at a bypass section between the pump and the solution tank. Details of the testing procedure and flow loop design can be found elsewhere.$^2$,$^7$

Although, the flow loop setup and flow condition in erosion testing is identical to step #1, the test solution used for wet erosion testing consists of distilled water only and Nitrogen gas is used instead of CO$_2$ gas. Nitrogen gas was used to prevent any corrosion during erosion experiments. Erosion of pre-formed scale specimens were measured by weight loss method at a temperature of 175 °F (79 °C), an oxygen concentration less than 15 ppb, a flow velocity of 14.0 ft/s (4.25 m/s), 20 psi (137.895 kPa) N$_2$ gas pressure and 0.4%wt solid particle concentration.

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* Trade Name

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After quantifying the erosivity of both kinds of particles, erosion-corrosion tests were conducted on pre-formed iron carbonate scale and bare steel specimens (step #3). These tests were also performed using the single test cell flow loop.

The test solution for erosion-corrosion experiments is prepared by mixing 5 gallons of distilled water with 3% wt. Sodium Chloride (NaCl), and 1500 ppm of sodium bicarbonate (NaHCO₃). Erosion-corrosion experiments were conducted at a pH of 5.9, temperature of 175 °F, an oxygen concentration less than 15 ppb, 0.4% wt. solid particle concentration, 20 psi (137.895 kPa) CO₂ gas and a flow velocity of 14.0 ft/s (4.25 m/s). In addition to LPR, the weight loss method was also used in erosion-corrosion tests. The role of LPR method was to quantify the corrosion part of erosion-corrosion. In erosion-corrosion test of pre-formed iron carbonate scale specimens, solid particles were added into the system after about 14 hours from the start of the test. During this time, the corrosion rate was monitored through LPR method to confirm that iron carbonate scale was protective. However, for erosion-corrosion tests of bare carbon steel specimens, solid particles were added at the beginning of the test. Erosion-corrosion tests were conducted with two kinds of solid particles, a 150 µm sand and a 250 µm CaCO₃. Each of these particles were tested separately. In addition to solid particles concentration monitoring, iron concentrations were also monitored using a colorimetric method (VACUettes Iron R-6001B**). The total erosion-corrosion damage to the samples were measured through weight loss method. This simply can be done by weighing the specimen before and after the erosion-corrosion test.

Inhibited erosion-corrosion experiments were finally conducted using the single test cell flow loop on bare carbon steel specimens (step#4). Experiments in this step (step #4) were conducted using the same procedure followed in step #3. However, imidazoline based inhibitor of known concentration was pre-mixed with the test solution to study the influence of inhibitor in reducing erosion-corrosion as compared to erosion-corrosion control/protection through iron carbonate scale formation. Inhibitor of different concentrations was introduced into the system through the sand feeder.

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RESULTS

In this section, results for iron carbonate scale formation, erosivity of CaCO\textsubscript{3} and sand particles, erosion-corrosion behavior of protective iron carbonate (FeCO\textsubscript{3}) scale covered and non-covered (bare) carbon steel material, and inhibited erosion-corrosion of bare carbon steel material.

Scale formation

Figure 4 shows an example of the LPR data obtained during iron carbonate scale formation. The drop in LPR corrosion rate that takes place at about 30 hrs indicates the start of iron carbonate scale formation. The LPR data indicates that this scale provides steady state corrosion rate of about 0.694 mm/y (30 mpy). The composition of iron carbonate scale was confirmed using X-ray diffraction analysis, as shown in Figure 5. In addition of iron carbonate scale, the obtained diffraction spectrum also indicates that iron carbide (Fe\textsubscript{3}C) was also present on the surface of the probe. Scanning electron microscopy (SEM) and visual images for the specimen surface at the end of the test, shown as insets in Figure 4, also indicate iron carbonate scale formation. An iron concentration of 15 ppm was measured at the end of the iron carbonate scale tests.

![Figure 4: LPR data for iron carbonate scale formation at 175°F, pH 5.9 and 9.0 ft/s flow velocity](image)
Figure 5: XRD analysis for iron carbonate scale formed at 175°F, pH 5.9 and 9.0 ft/s flow velocity

Erosivity of CaCO$_3$ and sand particles

Erosivity of CaCO$_3$ and sand particles were characterized under dry and wet conditions. Dry erosion tests were conducted on both bare carbon steel specimens and pre-formed iron carbonate scale. The tests were performed with a particle velocity of 23 m/s, and 30-degree impact angle for both particle types. The dry erosion behavior of bare steel with both sand and CaCO$_3$ particles, shown in Figure 6, exhibits a linear increase of cumulative mass loss with increasing mass of solid particles. However, sand resulted in one order of magnitude higher erosion ratio (slope of the line through data) than CaCO$_3$ particles.

Figure 6: Dry erosion behavior of carbon steel (UNS G10180) with sand and CaCO$_3$ particles at 23.0 m/s particle impact velocity and 30-degree impact angle

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The dry erosion behaviors of iron carbonate scale at 23 m/s particle velocity and 30-degree impact angle with sand and CaCO\textsubscript{3} particles are shown in Figure 7. As expected, iron carbonate scale exhibits different erosion behavior than carbon steel, because of the brittle nature of iron carbonate scale. The dry erosion behavior of pre-formed iron carbonate scale with sand shows a general increase in cumulative mass loss of iron carbonate scale with broadly non-linear behavior. On the other hand, dry erosion with CaCO\textsubscript{3} of pre-formed iron carbonate scale has three general erosion regions. The first region is in the range from 0 to 70 grams of CaCO\textsubscript{3}. The second region is in the range from 70 grams to 700 grams of CaCO\textsubscript{3} and the third region is in the range from 700 to 3500 grams of CaCO\textsubscript{3}. The first region also exhibited non-linear behavior, and a rapid increase in the mass loss with increasing amount of CaCO\textsubscript{3} particles. This behavior was associated with the erosion of the iron carbonate scale. The erosion ratio of the iron carbonate scale was determined based on this region. The second region, known as the transition region, has a mass loss rate of iron carbonate scale less than the mass loss rate in the first region. The second region also showed non-linear mass-loss behavior. In the third region, the mass loss rate is much slower than the initial region and linear behavior similar to that of the erosion of bare steel with CaCO\textsubscript{3} particles was observed. An example of the specimen surface at the end of dry erosion tests are shown as insets in Figure 7. By comparing erosion ratios for sand and CaCO\textsubscript{3} particles, it was found that sand erodes iron carbonate scale three times higher than CaCO\textsubscript{3}.

Figure 7: Dry erosion behavior of iron carbonate scale (formed at pH 5.9, 175˚F, 9.0 ft/s flow) with sand and CaCO\textsubscript{3} particles at 23.0 m/s particle impact velocity and 30-degree impact angle

Erosion tests were also conducted under wet, submerged direct impingement conditions with the objective of identifying erositvity of sand and CaCO\textsubscript{3} particles for iron carbonate scale as well as for improving the understanding of the erosion-corrosion mechanism under similar flow conditions for both wet and dry. A set of erosion tests were performed using the single flow loop under submerged direct impingement jet flow. Table 1 presents the weight loss results obtained from these tests. Results in Table 1 and the specimen surface at the end of these tests shown in Figure 8 indicate that it takes longer for CaCO\textsubscript{3} particles to cause erosion damage to iron...
carbonate scale similar to that of sand. Consequently, sand is also more erosive than CaCO₃ under wet conditions, as expected.

**Figure 8:** Pre-formed iron carbonate scale specimen surface after submerged wet erosion with (a) CaCO₃ and (b) sand particles

<table>
<thead>
<tr>
<th>Type of Particles (# of tests)</th>
<th>Erosion Time (hrs)</th>
<th>Mass Loss (mg ± Stdev)</th>
<th>Erosion Rate (mm/y)</th>
<th>Erosion Ratio (g/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃ (3)</td>
<td>2</td>
<td>53.4 ± 0.84</td>
<td>76</td>
<td>1.24E-05</td>
</tr>
<tr>
<td>Sand (3)</td>
<td>1</td>
<td>51.4 ± 1.47</td>
<td>144</td>
<td>2.32E-05</td>
</tr>
</tbody>
</table>

**Table 1**

Mass loss data shows the erosion behavior of iron carbonate scale under wet submerged direct imingement condition

Erosion-corrosion of protective FeCO₃ covered and non-covered carbon steel

As mentioned earlier in this paper, erosion-corrosion experiments were performed under two conditions. The first condition involves investigating erosion-corrosion of FeCO₃ covered carbon steel specimens, and second condition involves studying erosion-corrosion of bare steel surface specimens.

Erosion-corrosion experiments under the first condition were conducted with the objective of studying the performance of protective FeCO₃ scale in reducing CO₂ corrosion in presence of sand versus CaCO₃ particles. The LPR data obtained from such tests are illustrated in Figure 9. Each kind of particles were tested separately. At beginning of these tests, before solid particles were introduced, the scale was protective and a steady state corrosion of about 0.694 mm/y (30 mpy) was measured. When solid particles were added, corrosion rate increased reaching a steady state corrosion rate of approximately 9.6 mm/y (370 mpy) for system with sand and about 3.8 mm/y (150 mpy) for the system containing CaCO₃ particles. This increase in corrosion rate takes place because of the removal of iron carbonate scale by solid particle erosion. The image of the specimen surface at the end of each test are shown as insets in Figure 9. These images clearly show the FeCO₃ scale removal. Iron concentration was monitored throughout the erosion-corrosion tests. An iron concentration of about 0 ppm was measured for both systems before adding solid particles. However, iron concentrations of 10 ppm and 5 ppm were measured at the end of erosion-corrosion tests with sand and CaCO₃ particles respectively. Table 2 summarizes metal loss rate data obtained from LPR and WL methods for both sand and CaCO₃ particles. These erosion-corrosion data are repeatable, and consistent with other tests conducted at the same environmental conditions.
Figure 9: LPR data for erosion-corrosion of pre-formed FeCO₃ carbon steel specimens with sand versus CaCO₃ particles at a temperature of 175°F, pH 5.9, 3% wt. NaCl, 14.0 ft/s flow velocity, and 0.4% wt. of particles concentration.

Table 2
Summary of metal loss data from erosion-corrosion experiments of preformed FeCO₃ carbon steel specimens with sand versus CaCO₃ at a temperature of 175°F, pH 5.9, 3% wt. NaCl, 14.0 ft/s flow velocity, and 0.4% wt. of particles concentration.

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Average Corrosion Rate (mm/y); (n=3) (Sand)</th>
<th>Steady State Corrosion Rate (mm/y); (n=3) (CaCO₃)</th>
<th>Total Erosion-Corrosion Rate (mm/y); (n=3) (CaCO₃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPR</td>
<td>5.89 ± 0.33</td>
<td>9.37 ± 0.55</td>
<td>6.47 ± 0.35</td>
</tr>
<tr>
<td>WL</td>
<td>2.49 ± 0.22</td>
<td>3.96 ± 0.25</td>
<td>3.78 ± 0.25</td>
</tr>
</tbody>
</table>

By comparing the LPR behavior observed during tests with sand versus CaCO₃, shown in Figure 9, it can be determined that the erosion-corrosion with sand resulted in a steady state corrosion twice as high as the same system with CaCO₃ particles. The sand to CaCO₃ particles ratio in erosion-corrosion is very close to same ratio obtained for wet erosion case, which is about 1.89. Consequently, erosion-corrosion damage of scale covered steel can be correlated to wet erosion damage.

Another way of quantifying erosion-corrosion of iron carbonate scale was by considering the impingement zone area at the end of each experiment. Figure 10 shows two images, the image on the left (Figure 10a) is the impingement for the sand system and the image on the right (Figure 10b) is the impingement zone for the CaCO₃ system. The impingement zone for the sand system is clearly larger than the impingement zone for CaCO₃ system. This difference could be due to the impact angle of the particle types, CFD simulation indicates that the CaCO₃...
particles tend to impact closer to 90 degrees than the sand particles. Thus, it is likely that more concentrated erosion pattern on the CaCO$_3$ sample is due to a combination of the lower erosivity of these particles, and the higher impact angles of the particles. Details of the CFD simulation results are presented elsewhere.\textsuperscript{10}

![Image](image1.png)

**Figure 10:** The impingement zone areas for 150 µm sand (a) and 250 µm CaCO$_3$ (b) after erosion-corrosion tests

After conducting erosion-corrosion of the first condition, and prior to conducting inhabited erosion-corrosion tests on bare carbon steel material, erosion-corrosion tests were performed on bare steel in order to quantify the erosion-corrosion behavior of carbon steel material with sand versus CaCO$_3$ particles. These tests were performed to serve as a baseline for comparison with the erosion-corrosion behavior of iron carbonate scale covered carbon steel as well as for comparison with inhibited erosion-corrosion. Figure 11 illustrates LPR data obtained from erosion-corrosion tests of bare carbon steel material.

![Image](image2.png)

**Figure 11:** LPR data for erosion-corrosion of bare carbon steel specimens with sand versus CaCO$_3$ particles at a temperature of 175˚F, pH 5.9, 3% wt. NaCl, 14.0 ft/s flow velocity, and 0.4% wt. of particles concentration.

Separate tests were conducted for CaCO$_3$ particles and sand particles. In these tests, sand and CaCO$_3$ particles were added at the start of the tests to understand how the presences of these
particles influenced the corrosion behavior. The LPR corrosion rate in Figure 11 was initially about 5 mm/y (196 mpy) for both tests and then increased until it reached a steady state corrosion rate of approximately 25 mm/y (984 mpy) for system containing sand, and approximately 19.54 mm/y (769 mpy) for system containing CaCO$_3$ particles. These experiments were repeated at least three times to insure repeatability of the results. Although the environmental conditions of these tests promote FeCO$_3$ formation, no protective FeCO$_3$ scale was found covering the specimen surface at the end of these tests. An image of the specimens' surface at the end of these tests are shown as insets in Figure 11. An iron concentration of 20 ppm was measured for the system containing sand and an iron concentration of 15 ppm was measured for the system containing CaCO$_3$ particles. Table 3 summarizes metal loss rate data obtained from LPR and WL methods for both sand and CaCO$_3$ particles. Table 3 indicates that for both sand and CaCO$_3$ particles, the total erosion-corrosion rate is about 3 mm/y (118 mpy) less than corrosion part of erosion-corrosion, indicated by average LPR corrosion rate. The difference is likely due to iron carbonate scale beginning to form over carbon steel surface during these tests, but the solid particle erosion prevented significant FeCO$_3$ adhesion to the steel surface. This behavior is called synergism, which is the interaction between erosion and corrosion.

**Table 3**

Summary of metal loss data from erosion-corrosion experiments of bare carbon steel specimens with sand versus CaCO$_3$ at a temperature of 175˚F, pH 5.9, 3% wt. NaCl, 14.0 ft/s flow velocity, and 0.4 % wt. of particles concentration.

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Average Corrosion Rate</th>
<th>Steady State Corrosion Rate</th>
<th>Total Erosion-Corrosion Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LPR</strong></td>
<td>21.64 ± 1.15 (n=3) (Sand)</td>
<td>23.83 ± 0.51 (n=3) (Sand)</td>
<td>20.21 ± 0.35 (n=3) (Sand)</td>
</tr>
<tr>
<td><strong>WL</strong></td>
<td>20.21 ± 0.35 (n=3) (Sand)</td>
<td>19.54 ± 0.22 (n=3) (CaCO$_3$)</td>
<td>16.08 ± 0.47 (n=3) (CaCO$_3$)</td>
</tr>
</tbody>
</table>

Comparing the LPR and WL data of sand versus CaCO$_3$ in Table 3, it can be determined that the erosion-corrosion with CaCO$_3$ resulted in a metal loss rate of about 25% less than the same system with sand. This indicates that CaCO$_3$ particles cause less erosion-corrosion to bare carbon steel than sand. However, CaCO$_3$ particles still caused considerable erosion-corrosion damage under this environmental condition.

Comparing erosion-corrosion of bare carbon steel material with FeCO$_3$ covered steel, it can be found that FeCO$_3$ resulted in about 70% and 75% less erosion-corrosion than bare steel for sand and CaCO$_3$ particles respectively. Consequently, FeCO$_3$ reduces erosion-corrosion damage of carbon steel material under this environmental condition.

**Inhibited erosion-corrosion of bare carbon steel**

A limited number of inhibited erosion-corrosion tests were conducted to investigate the performance of an imidazoline inhibitor in reducing CO$_2$ corrosion in presence of CaCO$_3$ particles. Companion tests were also conducted using sand to compare the erosion-corrosion behavior of the inhibited system with these particles. The imidazoline based inhibitor investigated in this research is water soluble-oil dispersible. In these tests, a 50 ppm inhibitor concentration was investigated. Test were carried out on bare steel specimens, and solid particles were introduced into each corresponding system (sand/CaCO$_3$) at the start of the test. Figure 12 compares the LPR-measured corrosion rates for an inhibited system containing sand,
and LPR-measured corrosion rates for an inhibited system containing CaCO$_3$ particles. The LPR traces represent only the corrosion component of inhibited erosion-corrosion.

Figure 12: LPR data for inhibited erosion-corrosion of bare carbon steel specimens with sand versus CaCO$_3$ particles at a temperature of 175°F, pH 5.9, 3% wt. NaCl, 14.0 ft/s flow velocity, 0.4% wt. of particles, and 50 ppm inhibitor concentration.

Figure 12 indicates that LPR-measured corrosion rates started levelling off and reaching a steady state corrosion after 5 hours of exposure. The inhibited system with sand resulted in a steady state corrosion of about 0.17 mm/y (6.69 mpy), while the system with CaCO$_3$ particles resulted in a steady state corrosion of about 0.15 mm/y (5.90 mpy). As expected, no protective iron carbonate scale was found on either specimen surface at the end of these tests, as that shown by the insets of Figure 12. Table 4 summarizes metal loss rate data obtained from LPR and WL methods for both sand and CaCO$_3$ particles. Data in Table 3 indicates that for both sand and CaCO$_3$ systems, the total inhibited erosion-corrosion rate is significantly higher than corrosion part of inhibited erosion-corrosion. This means that the interaction between erosion and corrosion for the inhibited system is negligible.

Table 4
Summary of metal loss data from inhibited erosion-corrosion experiments of bare carbon steel specimens with sand versus CaCO$_3$ at a temperature of 175°F, pH 5.9, 3% wt. NaCl, 14.0 ft/s flow velocity, and 0.4% wt. of particles concentration.

<table>
<thead>
<tr>
<th>Measurement Method</th>
<th>Average (mm/y); (Sand)</th>
<th>Steady State (mm/y); (Sand)</th>
<th>Total Erosion-Corrosion Rate (mm/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average LPR</td>
<td>0.18</td>
<td>0.17</td>
<td>0.83</td>
</tr>
<tr>
<td>Average WL</td>
<td>0.16</td>
<td>0.15</td>
<td>0.635</td>
</tr>
</tbody>
</table>

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Comparing the LPR data of sand versus CaCO$_3$ in Table 4, it can be determined that the erosion-corrosion with CaCO$_3$ resulted in a metal loss rate of about 10% less than the same system with sand. This difference is insignificant, since the corrosion rates of both particles sand and CaCO$_3$ are low.

Comparing erosion-corrosion of bare carbon steel material containing 50 ppm inhibitor with FeCO$_3$ covered steel, it can be found that inhibited system resulted in about 87% and 84% less erosion-corrosion than FeCO$_3$ covered carbon steel for sand and CaCO$_3$ particles respectively. Consequently, inhibitor provides more protection for carbon steel material than FeCO$_3$ scale under this environmental condition.

CONCLUSIONS

The main objective of this study was to experimentally characterize the erosion-corrosion behavior of low carbon steel material when protected by iron carbonate scale or corrosion inhibitor as it was impinged by CaCO$_3$ particles or sand. This objective demanded the initial formation of iron carbonate scale, and conducting dry erosion, submerged wet erosion, and erosion-corrosion tests. The corrosion product layer formed at pH of 5.9, temperature of 175˚F and flow velocity of 9.0 ft/s was protective against CO$_2$ corrosion. XRD data showed that this surface layer contains both iron carbonate (FeCO$_3$) and iron carbide (Fe$_3$C). Dry erosion data showed that sand is more erosive than CaCO$_3$ particles for both bare steel and iron carbonate scale. However, CaCO$_3$ is sufficient to cause considerable erosion of the iron carbonate scale. Erosion-corrosion for carbon steel covered by iron carbonate scale with 150 µm sand is twice as high as erosion-corrosion with 250 µm CaCO$_3$ particles. However, the 250 µm CaCO$_3$ particles cause considerably high erosion-corrosion damage to the iron carbonate scale covered carbon steel. For the environmental conditions considered in this study, comparable sand to CaCO$_3$ ratios were obtained for erosion-corrosion and wet erosion. Thus, erosion-corrosion can be predicted based on wet erosion data.

For 50 ppm of imidazoline based inhibitor, inhibited erosion-corrosion data indicates that CaCO$_3$ particles resulted in comparable inhibitor performance to that of sand particles. Inhibited system resulted in a higher protection against CO$_2$ corrosion than iron carbonate scale for both kinds of particles.

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